Building and Environment 143 (2018) 15–23

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

10 Questions

Ten questions concerning cost-effective energy and carbon emissions optimization in building renovation

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ARTICLE INFO

Keywords:
Cost-effective building renovation
Carbon emissions reduction
Co-benefits
Energy savings

ABSTRACT

In European countries, buildings are the major energy consumers due to the general low energy performance of the existing building stock. To achieve the ambitioned targets for emissions reduction, it will be necessary to take actions for its large scale renovation. However, today's standards are mainly focused on new buildings, guiding the improvement of the energy performance of the existing buildings into expensive processes and complex procedures that seldom are accepted by users, owners or promoters. For these buildings, the range of technical solutions is shorter and may lead to ancillary works that result in a relevant increase in costs.

In this context, the IEA EBC Programme launched the Annex56 project, with the goal of investigating solutions and produce guidance suitable for European residential buildings, taking into consideration not only the benefits related to energy and emissions reduction, but also the added value resulting from the renovation process. Considering the goal of reducing emissions, measures that promote the use of renewable energy can be as effective as energy efficiency measures, therefore, it is important to determine the optimal balance between the minimization of energy demand and the use of renewable energy.

The optimization process has to explore the full range of cost-effective reduction of emissions and energy use and also to take into account the additional benefits and the overall added value achieved by the building within the renovation process as well as the increasing relevance of the embodied energy associated to the materials and systems used in the interventions.

1. Introduction

Significant changes are on-going regarding the type and quantity of energy that is being consumed, with different energy strategies being driven to attain particular policy objectives, depending on the country context [1–5].

Key strategic elements are the gradual transformation of the energy systems from fossil fuels to renewable energy (RE), the increase of the efficiency of the energy systems, the reduction of the energy use by the consumers, the creation of fully integrated energy markets and the removal of unnecessary regulatory or technical barriers. In many developed countries, the renovation of the existing building stock is a relevant and necessary action to put these strategies on the move, but although these buildings represent a significant potential in these areas [6] it has been found hard to fully exploit this potential.

Up to now, strategies to improve the energy performance in the building sector were largely focused on tapping and developing efficiency potentials of new buildings and more specifically on improving the building envelope. As for example, the EPBD and its recast [7] are putting a high emphasis on the high-energy performance of the building, although the deployment of RE is also addressed as a second step [8]. However, in most developed countries, the majority of the existing building stock has more than twenty years and presents low energy performance. Most of these buildings may not be able to reach the new energy standards due to design and construction constraints [9].

Given the major challenge of mitigating climate change and the important share of carbon emissions caused by energy consumption in existing buildings, reducing carbon emissions within building renovations is an important objective and probably the most important one. Up to now, standards for building renovation have focused mainly on the reduction of energy use through energy efficiency (EE) measures. However, given the barriers that building renovation faces, it is interesting to compare the effects of measures to increase EE with measures to increase the share of RE sources used in the building. In this context, the optimization of energy consumption and carbon emissions reduction is a goal that must be pursued in energy related building renovations.

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https://doi.org/10.1016/j.buildenv.2018.06.036
Received 29 April 2018; Received in revised form 6 June 2018; Accepted 13 June 2018
Available online 27 June 2018
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Given the ambitious but necessary climate change mitigation goals [10], cost-optimality is clearly not enough. It is necessary to exploit the possibilities of going beyond the cost-optimal level until the limit of the cost-effective reduction of energy and carbon emissions [9], integrate, when relevant, embodied energy use in the lifecycle impact assessment [11] and also considering the additional benefits (co-benefits) and the overall added value achieved in the renovation process [12]. Additionally, it is crucial to provide information and guidance with relevant and useful recommendations for the main stakeholders, in particular for building owners and policymakers. Although the following questions and answers are in many aspects suitable for all the existing building stock, the supporting investigations and therefore the present paper are specifically targeting residential buildings which represent 75% of the European building stock and a more homogeneous group than non-residential buildings [13].

2. Ten questions (and answers) concerning cost-effective energy and carbon emissions optimization in building renovation

Question 1: "How to achieve the best performance with the minimal effort when renovating existing buildings?"

The development of scenarios for the renovation of existing buildings and the related decision-making process are complex tasks due to the various objectives (i.e. energy and emissions efficiency, indoor comfort, spatial quality, cost-effectiveness, etc.), which need to be met together with the involvement of various stakeholders.

Achieving the best performance in these processes means not only cost-effectively reduce emissions and energy consumption but also identifying global quality improvement, economic impact of the intervention, operating costs reductions and some co-benefits like comfort improvement (thermal, natural lighting, indoor air quality, acoustics, etc.), increased value of the building and less problems related to building physics. Minimal effort to achieve this performance means reducing investment costs and minimizing the intervention in the building and the users' disturbance.

Furthermore, each building is a portion of the global building sector in which there is a need for a drastic reduction of emissions considering the goals for climate change mitigation, hereby introducing a societal perspective to the building renovation process. So, underlying the possible scenarios for the renovation of existing buildings, a substantial reduction of emissions must always be a prerequisite.

Within this context, although necessary to assess the adequate strategy for each building, a common approach can be applied including three main elements: to take a life cycle perspective, to take adequately into account the emissions besides only the primary energy and finally to take into account the achievable co-benefits.

Regarding the time perspective, it is crucial that the analysis of the cost-effectiveness of a certain renovation measure or package of renovation measures is done using a cost/benefit analysis that considers the total lifespan of the building or the period for which the renovation is being planned [14]. The use of simplified calculation methods, such as the simple payback [15], does not take into account any benefits or costs that occur after the initial investment has been recovered and therefore tends to turn the cheapest solutions into the most attractive ones. This simplified analysis leads to the missed opportunity of effectively improving the buildings' energy performance, although it is frequently used in standards and national regulations [16].

Considering the reduction of primary energy and emissions, there is, in general, a large potential for cost-effective renovations that promote EE measures together with measures that encourage the use of RE sources. The measures to encourage the use of RE often have the potential to strongly reduce carbon emissions at lower costs than just EE measures [17] but important reasons remain to justify keeping carrying out EE measures. Among these reasons are synergies between the RE systems and the EE measures allowing the use of smaller systems, and assuring thermal comfort and other co-benefits that can result from those measures (such as the reduction of problems like humidity and mould).

At last, it is important to also take into account the achievable co-benefits resulting from the renovation measures. The renovation of the existing building stock, improving significantly its energy performance, can deliver a broad range of additional benefits to the inhabitants of the buildings and to society. However, the evaluation of the benefits from energy related renovation programmes and policies focusses mainly on energy savings, leading to the underestimation of the positive impacts of building renovation, which may lead to sub-optimal investment decisions and policy design. While co-benefits could act as a driver for building renovation, the problem is that they are not perceived adequately by the users benefitting from them or by the investors taking the renovation decisions. At the building level, relevant co-benefits exist like increased user comfort, fewer problems with humidity, improved aesthetics, etc., and these should be considered in the decision making process for building renovation. In fact, for private owners, investors and promoters, the value of a building depends on the willingness to pay by the customer whether in a sale process or in a rental one. In the case of energy related building renovation, this willingness to pay depends on the expectation of future reduced costs on energy bills and building operation, but also on other benefits not related to energy costs that result from energy related building renovation measures [18].

Summarizing, the assessment of building renovation scenarios, besides the physical characteristics of the building and its location, must also consider the interests and needs of the users and of the promoters of the intervention, and take into account the broader interests of the society by considering the role of each singular renovation to the global efforts to mitigate climate changes. The assessment of the renovation scenarios must be done considering a long-term approach, using a life cycle cost (LCC) assessment. In general, these procedures can be simplified and better performances achieved by combining EE measures with the use of RE produced onsite, potentially reducing the volume and depth of the renovation works. A minimum of EE measures that maximize the co-benefits and creates synergies with the RE measures is always necessary, but the shift to RE based systems is crucial for the cost-effectiveness of the intervention and mainly to achieve the necessary reductions of carbon emissions.

Question 2: "How far to go with energy conservation and efficiency measures?"

Regardless of the use of RE (even if their use can totally eliminate carbon emissions), EE measures should be carried out in the renovation process once they bring several relevant co-benefits [12]. Besides that, the combination of EE measures with a switch to RE creates synergies [17] and their effect on the reduction of energy and emissions is more certain on a long-term perspective [17].

Co-benefits are the effects (either positive or negative) beyond the energy savings and the reduction of carbon emissions that may arise from an energy-related building renovation. However, in the assessment of building renovation scenarios, these benefits are usually not taken into account, which contributes to the underestimation of the full value of improving or re-using a building [19]. Some of the most relevant co-benefits are the thermal comfort, reduction of problems related to building physics, noise reduction, reduced exposure to energy price fluctuations, aesthetics and architectural integration [20]. EE measures, when compared to measures involving RE sources, are the main source of co-benefits at the building level.

Carrying out EE measures in combination with a switch to RE creates synergies that increase cost-effectiveness, once the reduction of the energy use through EE measures, allows reducing the peak capacity of the heating system as well. This is a key driver for making many EE measures of the building envelope cost-effective in combination with a switch of the heating system. In the case of heat pumps, their efficiency is higher if the energy need is reduced once this means that the supply temperature in the heat distribution system can be kept lower, meaning

an additional factor strengthening synergies with EE measures. However, it must be stressed that the lifetime of EE measures on the building envelope is longer than the lifetime of RE systems, and their long-term effect is, therefore, more certain.

If benefits from EE measures are undeniable, the adequate depth of those interventions is not so clear. In order to improve a building's energy performance and maximize the reachable co-benefits, it is important to improve the energy performance of as many elements of the envelope as possible, preferably all. As an example, increasing the thickness of the wall's insulation from 12 cm to 30 cm has often less impact on energy savings than limiting the wall's insulation to 12 cm and adding 10 cm of insulation to the roof.

However, it is recommendable to choose ambitious EE levels in order not to miss opportunities within building renovation. Once insulation measures are carried out, it is usually not cost-effective anymore to add further insulation at a later stage, because the marginal cost/benefit ratio is then unfavourable [17].

As an additional parameter, it is necessary to have in mind the impact of embodied energy use and embodied emissions of renovation measures. Although these embodied impacts of renovation measures are smaller than for new buildings, they become important for high efficiency buildings and for buildings using RE or district heating with a low carbon emission factor. In these cases, the emissions reductions obtained are smaller and sometimes the additional embodied energy in materials and construction is higher than the corresponding savings during the time of service [11].

Summarizing, as existing buildings often have several building elements with low energy performance, a higher impact is achieved if several building elements are intervened in the renovation process than just acting on a single one. Additionally, EE measures are the source of many co-benefits, particularly those improving building quality, residents' comfort and physical wellbeing. To maximize the co-benefits, it is also more relevant to improve as many elements of the envelope as possible, than to significantly improve just a few of them. However, it is advisable to choose a high efficiency level as target if the energy performance of an element of the building envelope is improved since it is much cheaper to achieve a high standard of insulation for a certain building element in one step rather than to first insulate only to some extent and increase the energy performance at a later stage. The limit for this high insulation standard is given by its cost-effectiveness and by the balance between the embodied energy of materials and construction and the corresponding savings during the building service life.

Question 3: "How does the use of renewable energy sources affect the cost-optimal levels?"

Cost-optimality in energy related building renovation gained relevance with the calculation method introduced by the EC Delegated Regulation [21].

The first step in determining cost-optimal solutions in building renovation projects entails an assessment of different renovation measures for the building envelope and for the building systems. Single-renovation measures are combined into coherent combinations (or packages) of renovation measures. The application of each package creates a renovation scenario for that building. Different renovation scenarios have to be tested, involving improvements in the building envelope and the replacement of the heating, cooling and domestic hot water (DHW) systems. For each renovation scenario, the non-renewable primary energy use is calculated, as well as the net present value (NPV) of the global costs (including investment costs, maintenance costs and energy related costs) for the calculation period. The core of the cost optimal method is the identification of the energy performance level that allows achieving the lowest net present value of all costs, including investment costs and running costs for the life time of the renovated building.

Although the cost-optimal level of energy performance in building renovation varies with the characteristics of each building, with the costs of the renovation packages and with the local climate, the change of the heating, cooling and DHW systems (even for those using RE sources) does not affect significantly the cost-optimal renovation package for the envelope of the buildings.

In fact, several studies [17,22–24,39] show that the cost-optimal renovation packages for the envelope are, most of the times, the same, whatever the technical systems and energy source used.

This does not mean that the cost optimum remains the same in absolute terms, with equal costs, carbon emissions and primary energy use, independent of the choice of the technical systems; on the contrary, the cost optimal often differ quite strongly for different technical systems. Instead, it means that most often, the selection of the type of EE measures to reach a cost optimum can be done independently of the type of technical systems considered. Consequently, in many cases, there are no trade-offs between RE measures and EE measures and thus, it is often not necessary to differentiate the cost-optimality of EE measures with respect to different technical systems.

These observations indicate that for individual building owners, when financial resources are scarce and the technical systems are not at the end of their life time, it makes sense to develop a long-term strategy for a stepwise renovation, starting by the building envelope. It could mean, for example, to start by insulating the roof, and insulate the walls and replace the windows at a first stage, and switch to RE the next time the heating system needs to be replaced some years later.

For policymakers, these results show that the further development of the national definitions for the nearly-zero-energy buildings, namely with the establishment of a numerical indicator for the minimum energy performance and for the minimum percentage of RE that has to be included, has to be carefully considered in the case of building renovation. A significant flexibility in the way each building can achieve that numerical indicator, allowing a wide range of combinations of EE measures and the use of renewable sources according to the characteristics and constraints of these buildings, along with the possibility of stepwise renovation, seems to be the best way to promote a cost-effective transition of the existing building stock to a low carbon built environment scenario.

Question 4: "What is the difference between cost-optimality and cost-effectiveness in building renovation?"

In building renovation, cost-optimality refers to the renovation scenario that allows reaching the lowest global costs considering investment costs, maintenance and running costs until the end of the lifetime of the renovated building [7,21]. Cost-effective solutions comprise also solutions going beyond the cost optimal level allowing achieving more ambitious energy and carbon emission targets, with global costs higher than those related to the cost optimal level but below the costs associated to a reference scenario in which energy performance is not improved. The reference case refers to the initial situation of the building combined with measures that would be necessary just to restore the functionality of the building elements without improving its energy performance.

Fig. 1 shows a generic graphic definition of the cost optimality and cost-effectiveness in a standard life-cycle costs analysis and it is of utmost importance to highlight the difference between both. Among the possible energy related renovation solutions that are cost-effective (with respect to a reference case), the cost optimal solution is the one with the least LCC. The reference case is understood to refer to the initial situation of the building combined with measures that would be necessary just to restore the functionality of the building elements for another life cycle without improving its energy performance. On the other hand, cost-effective solutions comprise also solutions going beyond cost optimality allowing achieving more ambitious energy and carbon emission targets.

In the case of building renovation, cost-optimal energy related renovation measures usually do not yet allow achieving high levels of energy performance and reduced emissions, being in fact not very ambitious [25–27]. To reach the long term climate change mitigation objectives, it is crucial to obtain the largest possible impact from

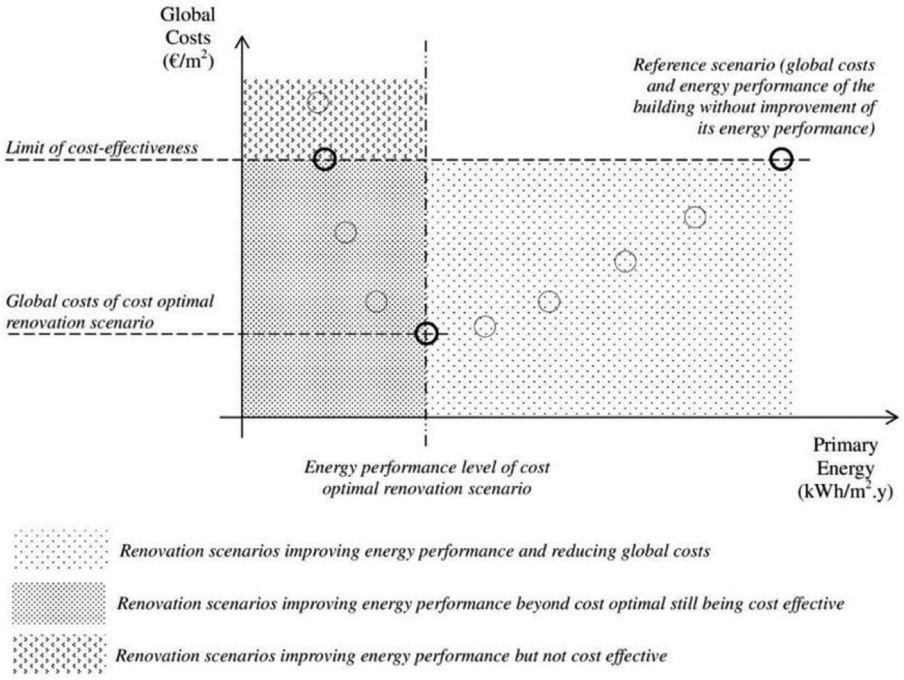
Global Costs (€/m²)
Reference scenario (global costs and energy performance of the building without improvement of its energy performance)
Limit of cost-effectiveness
Global costs of cost optimal renovation scenario
Energy performance level of cost optimal renovation scenario
Primary Energy (kWh/m².y)
Renovation scenarios improving energy performance and reducing global costs
Renovation scenarios improving energy performance beyond cost optimal still being cost effective
Renovation scenarios improving energy performance but not cost effective

Fig. 1. Identification of cost-optimal and cost-effective building renovation scenarios - corresponds to a renovation scenario.

building renovation in terms of contributing to the reduction of carbon emissions or primary energy use. Therefore, it is advisable to carry out the furthest reaching renovation packages which are still cost-effective compared to the reference case, rather than to be limited to the cost-optimal renovation package. Taking into account the co-benefits that can be achieved, the renovation measures that are considered to be cost-effective can be extended even further. However, given the relevant investments that are needed and the lack of cost-effectiveness in some cases, it is important that policymakers develop and make available financial schemes and incentives to promote this additional step.

Question 5: "How to integrate co-benefits in the decision making process of building renovation?"

One of the common problems associated with the evaluation of building renovation scenarios is that only the energy savings and the costs are considered, disregarding other relevant benefits and thus, significantly underestimating the full value of improvement and re-use of buildings at several levels of the economy [19]. Considering the reduction of energy use, emissions, and global costs as direct benefits resulting from energy related renovation measures, the notion of co-benefits refers to all the other positive or negative effects resulting from those renovation measures. In fact, renovation works improving the energy performance of the existing buildings trigger substantial co-benefits that can be felt not only at a financial level but also at the environmental and social levels [4]. This means that these interventions are able to promote the three pillars of sustainable development: economic development, social development, and environmental protection. These co-benefits can be felt at the building level [20] by the building owner or user (like increased user comfort, fewer problems with building physics, improved aesthetics), but also at the society level [28,29] (like health benefits, job creation, energy security, impact on climate change).

At the building level, the co-benefits relate to the concerns of owners, investors, promoters and users and mainly focus on the financial aspects relevant to these stakeholders, namely the reduction of the global cost of the renovation works and the increase of the maximum value of the building as well as on the individually perceived benefits by the stakeholders. The reduction of the global cost of the renovation works to the possible minimum corresponds to the cost optimal level. Theoretically, this tends to be the market based solutions if co-benefits are not taken into account. It is relevant that decision makers are fully aware of expected co-benefits of each possible renovation measure during the decision-making process, which might lead to more ambitious decisions beyond the cost optimal level.

The value of the co-benefits resulting from an energy related building renovation depends on the "beneficiary" or on the "perspective". From a macro-economic perspective, the co-benefits represent indirect benefits from investments in the improvement of the energy performance of buildings accruing to society at large. From a private perspective, the co-benefits represent the overall increment of the building value resulting from the renovation process, not explained by direct benefits. Private co-benefits report a value that depends on the beneficiary and on the context. Therefore, methods to determine and quantify these co-benefits rely on self-reporting surveys whose main purpose is to develop monetized estimates of the indirect impacts that can be assigned to the renovation measures [30]. For macro-economic co-benefits, their value does not depend on the valuation of the beneficiary and, theoretically, could be accounted by following and measuring the path of the effects of the energy related measures. Although the crossed impacts in different areas of the society make it impracticable to fully understand the scope of the effects in society, a growing number of attempts have been emerging in some areas where the impacts seem to be more relevant to the development of public policies [30,31].

These traditional methods are adequate for the evaluation of the results of large scale projects after they are in place, but show themselves burdensome, incompatible with a traditional decision-making process on small-scale rehabilitation projects for private owners. It is therefore needed to provide to these professionals and to the technicians that support them expeditious methods to include the co-benefits in their traditional decision-making process.

A possible method consists on comparing, in a life-cycle cost analysis, the cost optimal renovation package with other packages with better energy or emissions performance and check the additional co-benefits resulting from the packages beyond the cost optimal level, as exemplified in Fig. 2.

The decision on the package of renovation measures to be

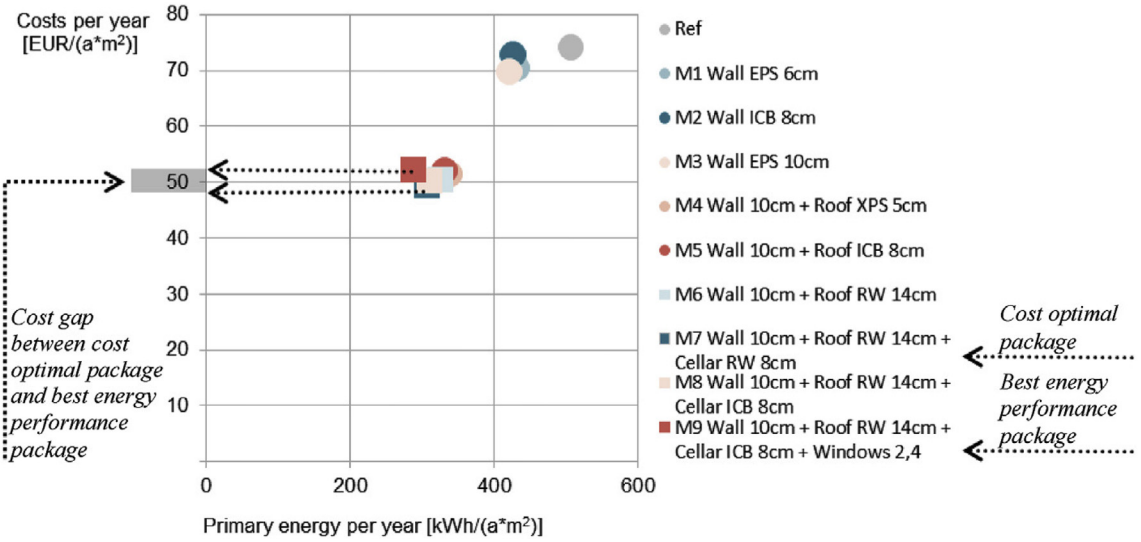
Costs per year [EUR/(a*m²)]
80
70
60
50
40
30
20
10
0
200
400
600
Primary energy per year [kWh/(a*m²)]
Cost gap between cost optimal package and best energy performance package
Ref
M1 Wall EPS 6cm
M2 Wall ICB 8cm
M3 Wall EPS 10cm
M4 Wall 10cm + Roof XPS 5cm
M5 Wall 10cm + Roof ICB 8cm
M6 Wall 10cm + Roof RW 14cm
M7 Wall 10cm + Roof RW 14cm + Cellar RW 8cm
M8 Wall 10cm + Roof RW 14cm + Cellar ICB 8cm
M9 Wall 10cm + Roof RW 14cm + Cellar ICB 8cm + Windows 2,4
Cost optimal package
Best energy performance package

Fig. 2. Comparison of cost-effectiveness of EE renovation measures and related impacts on primary energy.

implemented depends on the valuation of those additional co-benefits by the decision-maker. If the cost gap between the cost optimal and the best energy performance packages is lower than the willingness to pay, the rational option would be going for the best energy performance package.

Summarizing, from a global perspective, policymakers would benefit from gaining a deeper understanding of the dynamics at play in any investment in EE and RE sources, and subsequently, policy design and implementation can be adjusted to minimise undesirable impacts and maximizse prioritised impacts. It is the task of policymakers to consider any trade-offs between implementation and other costs of a particular policy related to EE and RE sources and the related socio-economic gains in welfare. Policymakers should create interdisciplinary teams to deal with the mechanisms by which the broader range of benefits can be measured and monetizsed, and propose how they can be integrated into policy development and evaluation, to support their efforts in optimising the potential value of EE and the use of RE sources.

For building owners and promoters, the value of a building depends on the customers' willingness to pay, whether in a sale process or in a rental one. In the case of energy related building renovation, this willingness to pay depends on the expectation of future reduced costs of energy bills and building operation, but also on other benefits not related with energy that result from EE measures and from the use of RE sources. Given the close relation between specific building renovation measures and co-benefits, those involved in the process of deciding among several possible packages of renovation measures should make use of strategies such as the above suggested to make options that consider the full added value from the renovation process. Given the holistic character of this approach and its ability to promote the three pillars of sustainable development, the use of sustainability certification systems like BREEAM [32], LEED [33], or DGNB [34] in the development of the renovation projects can be useful to increase the awareness of the full scope of benefits of the process.

Question 6: "Is life-cycle impact assessment (LCIA) relevant in building renovation?"

While building renovation does improve energy performance, it also increases the investment cost and the environmental impacts due to the new materials and building integrated technical systems added to the building. In this process, a question arises as to whether or not the embodied energy of the renovation materials and the related carbon emissions have a significant impact on the final primary energy use. When the renovation target is to achieve a very high energy performance building, a significant amount of material is added in order to significantly decrease its energy needs; beyond a certain level, the additional savings in energy use may be lower than the embodied energy of the materials being used. When the target is a nearly-zero energy building, where besides the very high energy performance there is a significant use of energy from renewable sources, the question is even more relevant if the non-renewable energy that could potentially be saved is very low.

A significant number of comparisons of the life-cycle costs analysis of renovation scenarios that consider only the operational energy and the same scenarios considering both the operational and the embodied energy, show that the inclusion of the embodied energy does not impact on the cost-effective and on the cost-optimal solutions [11,22]. On the other hand, in terms of total primary energy, the renovation scenario that leads to the lowest primary energy (in some cases approaching zero primary energy), changes when considering the embodied energy of the materials added due to differences in the environmental impacts of the insulation materials used in the renovation scenarios with very low operational energy. These observations are a result of an investigation carried out in Refs. [11,22] that included different types of buildings located in different European countries (from North, Central and South Europe) and using different energy sources, allowing to generalize the conclusions from those observations.

Therefore, embodied energy and embodied carbon emissions aren't very influential in the building renovation when the focus is on cost-optimal renovation solutions. However, when the energy performance approaches nearly-zero energy or nearly-zero carbon emissions levels, the relative contribution of the embodied energy or of the embodied carbon emissions can become significant. These results indicate that in these cases, the primary energy and carbon emissions optimizsation for both new and existing buildings should be carried out using a life-cycle perspective that considers the embodied impacts.

In this context, LCIA is a relevant approach to be recommended in future policies and practices in renovation projects to assess the renovation measures over the life cycle of the building as more and more projects towards nearly-zero energy and carbon emissions renovations become cost-effective. However, LCIA can be a complex process due to the high number of impacts that is necessary to calculate. It is then recommendable that, for the case of building renovation, some simplifications are adopted. Considering the specific characteristics of the building renovation, only processes that make a relevant contribution to the total environmental impacts of renovated buildings, and that can be put into practice with a reasonable effort, are necessary to be included, namely life-cycle impacts of measures that affect the energy

performance of the building (thermal envelope, building technical systems, energy use for on-site production and delivered energy).

Question 7: "Why is the opportunity of making existing buildings more energy efficient often missed?"

The fulfilment of the energy and climate objectives for the year 2020 and for the year 2050 [10,35,36] requires major initiatives from the building sector. Energy renovations to improve EE, reduce carbon emissions and increase the RE use of the existing building stock are necessary but are not currently undertaken to the extent needed. Therefore, it is of great importance to study and analyse owners and residents' acceptance of major renovations of buildings. The acceptance, motivation, needs, obstacles and drivers of residents and decision makers such as investors, owners, planners and contractors, with respect to the renovation process, need to be characterized and understood.

The major barriers and drivers of decision-makers are related to the building context, regulatory and financial aspects, external factors and information, knowledge and socio-economic issues. Regarding the building context, the type of dwelling (single family house vs multifamily building) and ownership is often a constraint mainly due to the difficulties in obtaining the necessary consensus between the owners; another important constraint is regarding aesthetics and cultural heritage of buildings or neighbourhoods, which makes difficult to also find consensus about the best solution to implement. Other issues that are also frequently cited as barriers are the legal framework, the buildings codes and some municipal or regional regulations, which show that a specific regulatory framework to promote the effective energy renovation of buildings is needed. Referring to the financial aspects, the identified barriers are related to the economic viability of the intervention, lack of incentives, discount or interest rates, energy prices, or issues regarding the payback time [37]. Some drivers are also identified, namely tax incentives, support programmes, and the increase of the value of the property. Regarding the external factors, most of the aspects are considered as drivers, since considering the environmental impact of the building renovation, in particular their direct advantages in air pollution, noise, and climate, it is common for people to have the will to mitigate them by reducing the energy use. The topic information and knowledge can be divided into aspects that act as drivers and those that act as constraints. As drivers, it can be pointed out the expertise, information, know-how, experience and motivation of the technicians. The choice of the strategy for renovation, the choice of the contractor and the responsibility to be assigned to it, usually act as constraints. At last, from a socio-economic perspective, some aspects are clearly the drivers for the building renovation, in particular education and social condition of the owner. Nevertheless, there are some issues that are considered a barrier, such as low income (financial resources), lack of availability (in terms of time), social norms and values, the disturbance it may cause on the user, or even a longer or shorter housing perspective.

Another perspective is the perception of the renovation by the residents. Residents are the end consumers of the renovation process [38] and the results of a renovation have a direct impact on their daily living and quality of life. They are also influenced by the renovation works that can be very disturbing for those who remain in the building during the intervention [39]. But residents are very often not in the position to decide which measures will be taken and when or who will carry out the work, i.e. they do not control the situation.

The perception of which measures should be taken can also differ between landlords and residents. Residents tend to value more features that are visible and that also bring additional benefits (e.g. double glazing is valued because both the energy and the acoustic performances are improved) [40]. Hence, some EE measures will be perceived more beneficially than others, just by being visible and close to the residents' daily life. For residents, building renovation can introduce relevant impacts on the physical environment, namely on the indoor environmental quality (thermal comfort, indoor air quality [37], acoustic and lighting conditions) but also non-energy related benefits such as increased security and safety. A visible change in the outdoor environment can be important for the acceptance of the renovation as well.

Also relevant for the residents' acceptance of the renovation process is their participation/involvement in the process. Participation can be classified on an ascending scale from information (e.g. receiving a leaflet in the mailbox informing that a renovation will take place), through anchoring (e.g. being invited to give their opinion about the suggested changes or offered to choose colours on the walls), onto participating in the planning and further being involved in the decision-making and management process [41]. Lack of involvement can lead to low acceptance of the time established for the refurbishment [42] and of the associated inconveniences, such as noise [38].

Question 8: "How to put the renovation of existing buildings on track to reach the long term goals of mitigating the climate change?""

In its "Roadmap for moving to a competitive low carbon economy in 2050" [43], the European Commission established a long-term objective of decreasing carbon emissions levels for the building sector by 88%–91% in 2050, compared to 1990 levels. In order to achieve this target, the EU needs to tackle the existing building stock and to reduce its energy use in the long term.

Crucially, it remains unclear which specific actions and legislative measures are necessary at the EU level to reach long-term targets related to carbon emission reductions and energy savings. Similarly, the question remains open as to how the EU will ensure that the potential for energy savings from the building stock is going to be fully tapped.

The need for a drastic reduction of carbon emissions in the building sector, associated with its specific constraints, require changes in the approach to mitigating climate change in this sector. This new approach to the large-scale renovation of the existing building stock should rely on three major issues to be addressed:

i Buildings are in general long lasting structures and their renovation implies a life-cycle approach considering large investments and the development of long-term strategies;
ii Carbon emissions need to be considered in standards and target setting at the same level as energy [17];
iii Energy and carbon optimized building renovation usually has several side effects often yielding substantial additional benefits, which can be as important as energy cost savings. These co-benefits have to be identified and combined with the impacts of carbon emissions and energy reduction measures on the decision making process [12].

a) Life-cycle approach

Improving a building's energy performance and switching to RE, is not just a contribution to mitigating climate change and to save resources, but often also save costs. The analysis of the cost-effectiveness of a certain measure or renovation package of measures is done using a cost/benefit analysis where the total lifespan of the building or the period for which the renovation is being planned should be considered by using a LCC assessment. Costs and benefits of each alternative are analysed along their life time and expressed in annualized costs or net present value. It includes the investment costs, energy costs, operation and maintenance costs and any residual value of the building at the end of the period considered in the analysis. LCC analysis is an adequate approach because it accounts for all cash outflows and inflows over the period under analysis and it also discounts the value of the money to adjust the cash to its present value.

b) Carbon emissions in standards and targets setting

There is, in general, a large potential for cost-effective building renovations that reduce both carbon emissions and non-renewable primary energy use. Both EE measures and measures that promote the use of RE sources contribute to these objectives. RE measures often have the potential to reduce carbon emissions more strongly and at fewer costs

than EE measures. This underlines the importance of taking into account RE measures in future policymaking.

c) Co-benefits

The renovation of the existing building stock, improving significantly its energy performance, can deliver a broad range of additional benefits (co-benefits) to the inhabitants of the buildings and to society. However, the evaluation of the benefits from energy related renovation programmes and policies focusses mainly on energy savings, leading to the underestimation of the positive impacts of building renovation, which may lead to sub-optimal investment decisions and policy design.

While co-benefits could basically act as a driver for building renovation, the problem is that they are not perceived adequately by the users benefitting from them or by the investors taking the renovation decisions. The problem also extends to specialists supporting investment decisions: energy specialists tend to focus solely on energy-related effects such as primary energy consumption and costs, and professionals from other fields, such as health professionals, are unlikely to be consulted in the context of building renovations. This means that information to increase the perception of co-benefits, as well as interdisciplinary cooperation, is needed to fully take into account the extent of the non-energy benefits and to let them influence investment decisions and policy design.

Co-benefits of EE investments in the built environment can act as a supporting instrument to reach policy goals in several areas, being necessary to create awareness about various aspects of building renovation which are so far often not adequately taken into account, allowing for a better definition of upcoming standards, rules and regulations.

Question 9: "What main recommendations should be considered by building owners regarding building renovation?"

Considering the perspective of a cost-effective energy and carbon emissions optimization in building renovation as described in the first 8 Questions and Answers, various aspects of building renovation are often not adequately taken into account, leading to the loss of opportunities in performing optimized interventions in existing buildings. Therefore, in the development of their renovation projects, building owners should take into account the following recommendations:

Recommendation 1: Shift to technical systems based on RE

Before a conventional technical system is replaced, it is advisable to consider a switch to RE once in many cases this is not only environmentally but also economically attractive from a life-cycle perspective. Additionally, this switch provides the residents with a significant comfort and stability regarding future energy price fluctuations [12], [17].

Recommendation 2: Take advantage of synergies between the shift to RE and EE measures

The replacement of the heating and cooling systems is an excellent opportunity to carry out renovation measures on the building envelope as well, creating synergies. If carried out together, the investments in the building envelope result in savings on the investment costs for the technical systems, because the more energy efficient a building is, the smaller can be the dimension of the technical system [17].

Recommendation 3: Seize the opportunity of maintenance or repairing interventions

The need to renovate buildings' envelope or their technical installations represents an excellent opportunity for improving their energy performance. Many EE measures are profitable when an intervention on the related building elements is needed to restore their functionality. Such measures are for example repainting or repairing a wall or making a roof waterproof again. In such a case, the life-cycle costs of a scenario with an energy improvement of the building performance can be compared with a scenario in which only the functionalities are restored. The actual costs of the energy measures will then only comprise the difference between these two scenarios. If a renovation is not carried out at a time when such a renovation needs to be carried out, the cost-effectiveness of the energy related measures will be lower and it may take many years until the opportunity reappears [17].

Recommendation 4: Improve as many envelope elements as possible

Existing buildings often have several building elements with low efficiency performance. A higher impact is achieved if several building elements are involved in the building renovation process than just act on a single building element alone. Additionally, EE measures are the source of many co-benefits, particularly those improving building quality and the residents' comfort and physical wellbeing. To maximize the co-benefits, it is more relevant to improve many elements of the building envelope than to significantly improve just a few of them. However, it is advisable to choose a high efficiency level as target if the energy performance of an element of the building envelope is improved since it is much cheaper to achieve a high insulation standard for a certain building element in one step rather than to insulate first to some degree and to increase the energy performance at a later stage [12], [17].

Recommendation 5: Consider energy related building renovation as an opportunity to increase building value

The economic value of the existing building stock is an important asset, which can be potentiated in an optimized way. By saving future energy costs and providing several co-benefits, energy related building renovations increase the value of the renovated buildings [12].

Recommendation 6: Involve residents in the renovation process

In rented buildings, tenants should be involved in the renovation process, so that they can feel more engaged in that process, consider the renovation as positive and understand the long-term environmental benefits. Quite often, the relationship between owners and residents is critical for the acceptance of the latter towards building renovation. The relationship between them should be improved so that these two players can be more coordinated towards the motivations and benefits of building renovation [44].

Question 10: "What main recommendations should be considered by policymakers regarding building renovation?"

Considering the perspective of a cost-effective energy and carbon emissions optimization in building renovation as described in the first 8 Questions and Answers, for a better definition of upcoming standards, rules and regulations, policymakers should consider the following recommendations, focusing on three major vectors, namely strategic thinking in the development of energy policies, standard setting, and incentives:

Recommendation 1: Introduce carbon emissions targets in addition to energy targets

It is advisable to introduce a target to reach nearly zero carbon emissions in existing buildings undergoing a major renovation, complementing existing EE requirements. If this is not cost-effective because, for example, the heating system would not have to be replaced anyway in the near future, exceptions can be made or subsidies can be allocated for these cases considering the co-benefits from a macroeconomic perspective [12], [17].

Recommendation 2: Shift to technical systems based on RE

It is adequate to make a switch to RE mandatory when a heating system is replaced, similarly to energy improvements of the building envelope. Exemptions may still be granted from such a rule if the building owner can show that such a measure would not be cost-effective from a life-cycle perspective or subsidies can be allocated for these cases considering the co-benefits from a macroeconomic perspective. Exemptions could also be made if a building is connected to a district heating system which either already has a high share of RE or for which a plan exists to switch to RE. Due to the higher investment costs compared to conventional heating systems, it is recommended to design incentives or other financial mechanisms to support this shift [17].

Recommendation 3: Promote the combination of EE measures with RE

It is recommendable that standards and other policy measures, for example subsidies, create incentives to combine renovation measures on the building envelope with a replacement of the heating system, in order to make sure that reductions in energy use and emissions are achieved most efficiently. Exceptions could be made for buildings connected to a district heating system, which already has a high share of RE or for which a switch of the district heating system to RE sources is already planned [17].

Recommendation 4: Shift from cost-optimality to cost-effectiveness

It is recommendable that standards do not limit themselves to make an energy performance level mandatory up to the cost-optimal level but to make also further measures mandatory as long as they are cost-effective with respect to a reference case.

Depending on the original condition of the building, improving all elements of the building envelope often means going beyond the cost optimal level. However, in these circumstances, the packages of measures can remain cost-effective when compared to the reference case and the improvement of all elements of the building envelope is usually the way to maximize the added value achieved with the co-benefits [12,17].

Recommendation 5: Make use of all opportunities

It makes sense for standards for achieving improvements in energy performance to focus on the situation where one or more building elements are in need of renovation anyway. An understanding of the current status of the building stock is essential to clearly define the strategy and timing for building renovation [17].

Recommendation 6: Make regulations flexible

To most effectively achieve a large reduction in energy use and carbon emissions in existing buildings, it is important that standards, targets and policies take into account the complexity of building renovation while seeking for cost-effective solutions. Flexibility is needed to give renovation strategies a chance to enable the transformation of the building stock towards low energy use and a nearly zero emissions level. This includes the flexibility to reach these targets step by step over time [17], [45].

Recommendation 7: Whole building renovation is preferable instead of maximizing the energy performance of just one or few individual elements

In the existing building stock, buildings often have several building elements with low efficiency performance. A higher impact is achieved if several building elements are involved in the building renovation process than just act on a single building element alone. However, it is advisable to choose a high efficiency level as target if the energy performance of an element of the building envelope is improved since it is much cheaper to achieve a high insulation standard for a certain building element in one step rather than to insulate first to some degree and to increase the energy performance at a later stage. Additionally, EE measures are the source of many co-benefits, particularly those improving building quality and the resident's comfort and physical wellbeing. To maximize the co-benefits from energy related building renovation, it is more relevant to improve as many elements of the building envelope as possible than to significantly improve just a few of them [12], [17].

Recommendation 8: Assure inclusion of tenants in the building renovation processes

In rented buildings, tenants should be involved in the renovation process, so that they can feel more engaged in that process and consider the renovation as positive and understand the long-term environmental benefits.

Quite often, the relation between housing companies and residents is critical for the acceptance of the latter towards building renovation. The relationship between them should be improved, and policymakers should provide package solutions consisting of legislative changes, financial incentives and better dissemination of information [46], so that these two players can be more coordinated towards the motivations and benefits of building renovation [44].

3. Summary and conclusions

Climate change mitigation is a global major challenge and given the important share of carbon emissions caused by energy consumption in existing buildings, reducing carbon emissions within building renovations is crucial. Up to now, standards for building renovation have focused mainly on the reduction of energy use through EE measures. However, a broader perspective is necessary to achieve cost-effective energy and carbon emissions optimization in building renovation and to move towards the needed drastic reduction of carbon emissions in the building sector.

A new approach to the large-scale renovation of the existing building stock is necessary, including the technical perspective, the methodological approaches and the participation of the several stakeholders.

Technically, the combined use of EE measures with the use of RE produced onsite is crucial, not only for reducing the volume and depth of the renovation works but mainly to achieve the necessary reductions of carbon emissions.

Methodologically, the balance between these two types of measures has to take into account costs, energy, emissions, and also the co-benefits from the renovation in an optimization process that considers the particular characteristics of each building. A life-cycle approach has to be considered, taking also into account the embodied impacts, and the actual unambitious cost optimal levels must be replaced by a cost-effectiveness standard.

At last, the acceptance, motivation, needs, obstacles and drivers of residents and decision makers such as investors, owners, planners and contractors, with respect to the renovation process, need to be characterized and understood. All these stakeholders play a relevant role in the renovation process and strategic thinking in the development of energy policies, standard setting, and incentives by policymakers must take this into account.

4. Expertise of the authors

Manuela Almeida is a Civil Engineer with Ph.D. who has invested in a research carrier. Always connected to buildings and construction technics, she has started as a professor at the University of Minho and since then, she has been acting in different fields of research. From buildings energy and acoustic performance to buildings conservation and rehabilitation, her scientific contribution includes papers in specialized magazines, chapters of books and books. Her participation in national and international events has led to several technical productions as author and co-author. She is also a consultant and trainer for qualified experts in buildings thermal performance. Concerning the leadership, she has had different responsibilities within the Department of Civil Engineering and has been the operating agent of the IEA EBC Annex 56 related to Cost Effective Energy and Carbon Emissions Optimization in Building Renovation and is the operating agent of Annex 75 - Cost-effective Building Renovation at District Level Combining Energy Efficiency & Renewables.

Marco Ferreira is an Architect, currently finishing his Ph.D. with the title “Renovating the existing building stock to net zero energy”. He has been actively participating in the IEA EBC Annex 56 project, being the leader of the sub-task dealing with “Co-benefits of energy related building renovation”.

Acknowledgements

These Ten Questions paper is significantly supported by the results and conclusions of the research activities, outcomes and findings from IEA EBC Annex 56. The authors appreciate contributions from all participants of Annex 56 (http://www.iea-annex56.org/) as well as from IEA (International Energy Agency)'s Energy in Buildings and Communities (EBC) Programme (iea-ebc.org) Chair, Secretary, and the

executive committee. The work within IEA EBC is co-funded by different national authorities and the individually participating national organisations – universities and private companies.

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